

An eclipsing binary black hole candidate system in the blazar Mrk 421

E. Benítez,¹ J. I. Cabrera,^{2,3} N. Fraija,¹ X. Hernández,¹ O. López-Corona,^{1,4,5}
F. D. Lora-Clavijo,^{1,6} S. Mendoza.^{1*}

¹*Instituto de Astronomía, Universidad Nacional Autónoma de México, AP 70-264, Ciudad de México 04510, México*

²*Escuela Superior de Física y Matemáticas, Instituto Politécnico Nacional, U.P. Adolfo López Mateos, Ciudad de México 07730, México*

³*Facultad de Ciencias, Universidad Nacional Autónoma de México, Ciudad de México 04510, México*

⁴*Centro de Ciencias de la Complejidad, Universidad Nacional Autónoma de México, Ciudad de México 04510, México*

⁵*Instituto de Investigación sobre Desarrollo Sustentable y Equidad Social, Universidad Iberoamericana, Ciudad de México, México*

⁶*Grupo de Investigación en Relatividad y Gravitación, Escuela de Física, Universidad Industrial de Santander, A. A. 678, Bucaramanga 680002, Colombia*

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ABSTRACT

Removing outbursts from multiwavelength light curves of the blazar Mrk 421, we construct outburstless time series for this system. A model-independent power spectrum light curve analysis in the optical, hard X-ray and γ -rays for this outburstless state and also the full light-curves, show clear evidence for a periodicity of ≈ 310 days across all wavelengths studied. A subsequent full maximum likelihood analysis fitting an eclipse model confirms a periodicity of 310 ± 1 days. The power spectrum of the signal in the outburstless state of the source does not follow a flicker noise behaviour and so, the system producing it is not self-organised. This and the fact that the periodicity is better defined in the outburstless state, strongly suggests that it is not produced by any internal physical processes associated to the central engine. The simplest physical mechanism to which this periodicity could be ascribed is a dynamical effect produced by an orbiting supermassive black hole companion eclipsing the central engine. Interestingly, the optimal eclipse model infers a brightness enhancement of $(136.4 \pm 20)\%$, suggesting an eclipse resulting in a gravitational lensing brightening. Consistent with this interpretation, the eclipse occurs for only $(9.7 \pm 0.2)\%$ of the orbital period.

Key words: galaxies: quasars: individual: Mrk 421 – galaxies: quasars: supermassive black holes – methods: statistical

1 INTRODUCTION

Among active galactic nuclei, blazars are considered the most variable sources since they exhibit the most rapid and largest amplitude continuum variations extending from radio to X-rays, and many of them up to the γ -rays. The detection of variability in blazars is considered a valuable tool since it enables us to constrain properties associated with their central emission regions and set upper limits on the physical scale of the system through causality arguments (see e.g. Ulrich et al. 1997).

Several variability studies in blazars have been done with the aim of finding periodic or quasi-periodic variations, which could establish the presence of supermassive binary black hole systems (cf. Begelman et al. 1980). To date, the best known example of a binary black hole candidate asso-

ciated with a blazar is found in OJ 287, an object which shows a variability with period ~ 12 years. The periodicity was discovered by analysing its historical light curve comprising data for more than 100 years in the optical V band (see Sillanpää et al. 1988; Lehto & Valtonen 1996). This result led to the proposal of a precessing binary black hole model for OJ 287, which can reproduce the periodic outbursts displayed by this object. Recently, more blazars have been considered as supermassive black hole candidates (cf. Rieger 2007), and new results on quasi-periodical oscillations have been reported by e.g. Sandrinelli et al. (2016) and Ackermann et al. (2015).

Direct imaging of binary supermassive black hole systems in active galactic nuclei have been performed with great success in very few cases (see e.g. Deane et al. 2014, and references therein), ranging from the kiloparsec to the extreme ~ 5 pc separation scales. The small outburst to quiescent active galactic nuclei fraction raises the possibility of a large

* Email: sergio@astro.unam.mx

population of binary black holes remaining undetected, and highlights the importance of developing search techniques for such objects in the absence of outbursts.

Mrk 421 is a BL Lac object hosted by an elliptical galaxy and one of the most well studied blazars due to its proximity, with a redshift $z \approx 0.03$ (Ulrich et al. 1975). Although several multiwavelength variability studies have been done on Mrk 421 (see Abdo et al. 2011; Pian et al. 2014, and references therein), the light-curves obtained for this blazar (e.g. Liu et al. 1997; Chen et al. 2014) have not shown fully convincing evidence of periodic or quasi-periodic variations, potentially due to shortcomings in the statistical methods employed (Baluev 2015).

In this letter we model multiwavelength light curves of Mrk 421 using the free software R-package RobPer (Thieler et al. 2014), to analyse the associated periodograms on time scales of several years. The method is applied to what we define as “outburstless” light-curves, i.e. those curves where the signal coming from flares or outbursts have been removed. More precisely, we analyse the signal below the $3\text{-}\sigma$ noise level. In section 2 we present the multiwavelength database used for the analysis, and the corresponding periodograms obtained using RobPer. Once the existence of a ~ 310 days period was found through the periodogram analysis, a full maximum likelihood model for a generalised eclipse is introduced to recover the optimal frequency, phase, eclipse fraction and duration of the eclipse for the X-ray data. We interpret the result of a negative eclipse fraction and its small duration as evidence for a supermassive black hole companion orbiting about the central engine, which results in a brightening of the light curve. Finally, we present a discussion of our results in Section 3.

2 DATA ANALYSIS

The outburstless multifrequency light curves of the Blazar Mrk 421 were constructed using average fluxes to find the $3\text{-}\sigma$ level in three different wavebands. The optical long-term light curves analysed in this work were built using the database of the *American Association of Variable Star Observers* (AAVSO), from 1981 April 11 to 2014 July 21 (~ 33 years). Average V-band magnitudes, with no errors reported in the database, were obtained and converted to flux units in Jy. The X ray data from 15–50 keV were obtained using the database of the *SWIFT-BAT* hard X ray transient monitor (Krimm et al. 2013) from 2004 December 22 to 2014 May 3 (~ 10 years). *Fermi-LAT* γ -ray fluxes were obtained in the range 0.2–300 GeV using the public database. The data used covers the interval 2008 August 08 up to 2014 May 31 (~ 6 years), and were reduced following the procedure described in Cabrera et al. (2013).

Once the data above the $3\text{-}\sigma$ level are identified, it is replaced by blank intervals in the light curve. This generates the outburstless curves we further analyse. Thus, we study the signal which is usually discarded in studies of active galactic nuclei variability.

An important task in several astrophysical studies is the detection of periodicities in irregularly sampled time series, or data with low signal to noise ratios. Any periodic behaviour present in the observed data will be the result of any intrinsic variations of the system analysed, convolved

with any periodicity imposed by the temporal sampling of the various data observed. The use of three distinct energy bands, one from ground based observations and two from independent satellites, allows a handle on this aspect, as the time sampling of each is also independent and distinct. The physical relevance of any feature found in the frequency analysis will depend on whether it appears in all bands or not, and on whether it coincides or not with elements imposed by the respective spectral window functions of the data used (cf. Dawson & Fabrycky 2010).

The main problem associated with these measurements is that the classic Fourier periodogram analysis cannot be applied to irregularly sampled databases (e.g. Thieler et al. 2013a). For the same reasons, the Deeming (1975) periodogram is not adequate as it is known to react to periodicities in the sampling (see e.g. Hall et al. 2000). Hence, periodicity searches in this kind of time series have become a very active research field. In the case of light curves, the epoch folding periodogram (Leahy et al. 1983) or the analysis of variance periodogram (Schwarzenberg-Czerny 1989) can be interpreted as fitting a step function to a light curve. The other choice of preference is to use sine function implementations e.g. Lomb-Scargle (Scargle 1982) or the phase dispersion minimisation periodogram (Stellingwerf 1978). In principle, both classes work equivalently for unevenly sampled time series. More recent methods use uncentred data and fit a model with intercept (e.g. Cumming et al. 1999; Zechmeister & Kürster 2009). The R package RobPer (Thieler et al. 2013a), incorporates more complex periodic functions in the fitting process such as periodic splines (e.g. Gaidos et al. 1996; Oh et al. 2004) which provide more robust results. RobPer applies an outlier search on the periodogram, instead of using fixed critical values that are theoretically only justified in case of least squares regression. Among other special features, RobPer has a very complete pool of regression techniques, consisting of the classic least squares, least absolute deviations, least trimmed squares, M-, S- and τ -regressions. It optionally takes observational uncertainties into account using weighted regressions. As with any other type of periodogram the output represents the coefficient of determination for each trial frequency.

Due to the advanced capabilities of the RobPer package and the power and generality of the R project for Statistical Computing, we have analysed the multiwavelength light curves of Mrk 421 for the first time using this software. For this particular case, we use splines as test functions and the M-regression using the Huber function.

The top row of Figure 1 shows the full light curves analysed in the optical, X and γ -ray bands. The average flux level is shown by the solid horizontal line, and the $3\text{-}\sigma$ level by the dashed horizontal one, which defines the cut taken to construct the outburstless states. The middle row of the Figure presents the spectral window functions associated with the time structure of the sampling in the respective data sets. The first panel, corresponding to the optical data, is clearly dominated by a strong feature at a period of 365 days, inherent to the daytime appearance of Mrk 421 for approximately four months a year. The first significant peak in the X-ray spectral window function, at a period of 120 days, is produced by the three month gap common to many *SWIFT* sources (e.g. Stroh & Falcone 2013). A series of peaks follow

at well defined periods, including again a strong yearly feature. In the γ spectral window function we see a sequence of well defined peaks, crucially not coinciding with the ones in the X-rays. It is clear from the plots in the middle row of Figure 1 that the time structure of the sampling in the three bands used is highly independent.

The bottom row of Figure 1 shows the periodograms for the optical, X and γ -ray bands, respectively. In the optical, a number of peaks are evident, the largest at a period close to 310 days, distinct from the subsequent feature at 365 days. This last is a reflection of the time sampling structure evident in the middle row. A series of narrow peaks with periods below 190 days also appear in the ≈ 30 years covered by this data sample. The middle panel, a periodogram for the ≈ 10 years covered by the *SWIFT* data, has as its most prominent element a well defined signal at ≈ 310 days. Again, this is separate from the small features associated to the yearly enhancement in the corresponding window function. Other than this, a lower peak appears below 250 days. The last plot on the bottom row of the Figure shows the much shorter temporal extent of the ≈ 6 years in the γ -ray data yielding a prominent and broadened feature closely centred on 310 days, and two narrow peaks at 160 and 130 days.

Comparing particularly the left and middle plot of the bottom row in Figure 1 to their respective window functions, it is clear that the features at 310 days do not correspond to peaks imposed by the very distinct time sampling of the two data sets, as is also the case in the less well defined periodogram of the shorter time extent γ -ray data. Thus, the 310 day period is constant across bands, despite the widely changing and completely independent time sampling structures and observational setups. Outside of the period ranges shown in the middle and bottom rows of Figure 1 other peaks appear, but much broader, noisier, and not at fixed positions across observational bands.

We note that the window functions and periodograms of the full uncut light curves, including outbursts, differ little from the ones presented, which show a somewhat more clearly defined time structure. This shows that the periodicity detected is not associated to the outburst component, that which is usually analysed, but to the underlying outburstless state.

In general terms, a periodogram analysis not always yields straightforward confidence intervals. This is due to the fact that there is not a well established technique that considers the non-linear transformation of uncertainties when converting from the time to the frequency domains. This is also true when a periodicity is calculated directly in the time domain for data with low signal to noise ratio.

The power spectrum shows that the multiwavelength signal does not follow a flicker $1/f$ noise behaviour. Instead, a more correlated brown-like noise signal is detected; meaning that the physical processes responsible for this periodicity are not related to the central engine, which is typically associated with a self-organised $1/f$ signal (Per Bak & Wiesenfeld 1987; Sole et al. 1997; Press 1978; Kataoka et al. 2001; Boyer & López-Corona 2009; Corona et al. 2014). The most parsimonious interpretation of our results is provided by considering them as evidence suggesting an eclipsing supermassive binary black hole system.

From the RobPer analysis we have found a consistent periodicity in the outburstless signal with period of order ~ 310 days. In order to verify this result independently, we implemented a maximum likelihood analysis (e.g. Hernandez & Valls-Gabaud 2008) for a normalised Gaussian noise observed through a window eclipse function $e(t)$ for the high quality hard X-ray data. The lack of errors in the optical data, plus the shorter temporal extent of the γ -ray observations make the X-ray periodogram the one where the 310 feature is clearest. Therefore, the band we use for the further maximum likelihood analysis is the X-ray one. Whenever $\sin(\omega t + \phi)$, being ω , t and ϕ the frequency, time and phase respectively, exceeds a critical threshold parameter Θ such that $-1 \leq \Theta \leq 1$, the signal is reduced by an eclipse fraction f , otherwise the inherent Gaussian noise is unaffected, i.e.:

$$e(t) = \left[1 - \frac{|\Theta - \sin(\omega t + \phi)| f}{|1 - \Theta|} \right]. \quad (1)$$

The log-likelihood function is now given by:

$$\ln \mathcal{L}(T, \phi, f, \Theta; \{S_i, \Delta S_i\}) = \sum_i \frac{(S_i/e(t) - 1)^2}{2\Delta S_i^2}, \quad (2)$$

where S_i and ΔS_i are the normalised i -th measured signal value and its uncertainty, respectively, with a period $T := 2\pi/\omega$. A dense exploration of parameter space returns the following optimal parameters: $T = 310.54 \pm 1$, $\phi = 1.52 \pm 0.02$, $f = -0.0015 \pm 0.002$ and $\Theta = 0.954 \pm 0.002$. Given the X-ray data mean of 0.0011, the percentage eclipse fraction is given by 136.4 ± 20 .

The remarkable conclusion is that $f < 0$. Therefore the eclipse in fact corresponds to a slight brightness enhancement. It is tempting to identify this with the gravitational lensing effect of an eclipse by a super massive black hole companion, which would be consistent with the short inferred fractional duration of the eclipse of $(\arcsin(0.954 \pm 0.002) - \pi/2)/\pi = 9.7 \pm 0.2\%$. We see that a full maximum likelihood parametric modelling of the light curve allows to go beyond just periodicity, to gain a deeper insight into the physical characteristics of the system studied.

Note that even though a full sine curve was allowed by the maximum likelihood analysis, the optimal eclipse does not resemble a sine curve. This fact highlights the importance of considering very general periodic functions in the original periodogram analysis, as is the case for the RobPer package used here.

3 DISCUSSION

An established fact of Fourier periodogram analysis is that it cannot deal with irregularly sampled time series or with highly variable measurement accuracies (Thieler et al. 2013b), such as the optical light curves used in this work. To avoid the use of a Fourier frequency based analysis on the data, we used the R-package RobPer (Thieler et al. 2014).

The high frequency oscillation modes in all the light curves analysed in this work follow a white-like noise pattern and are thus not related to any self-organised phenomenon (Landa et al. 2011). This behaviour corresponds to micro-physical activity of the source, producing non-correlated

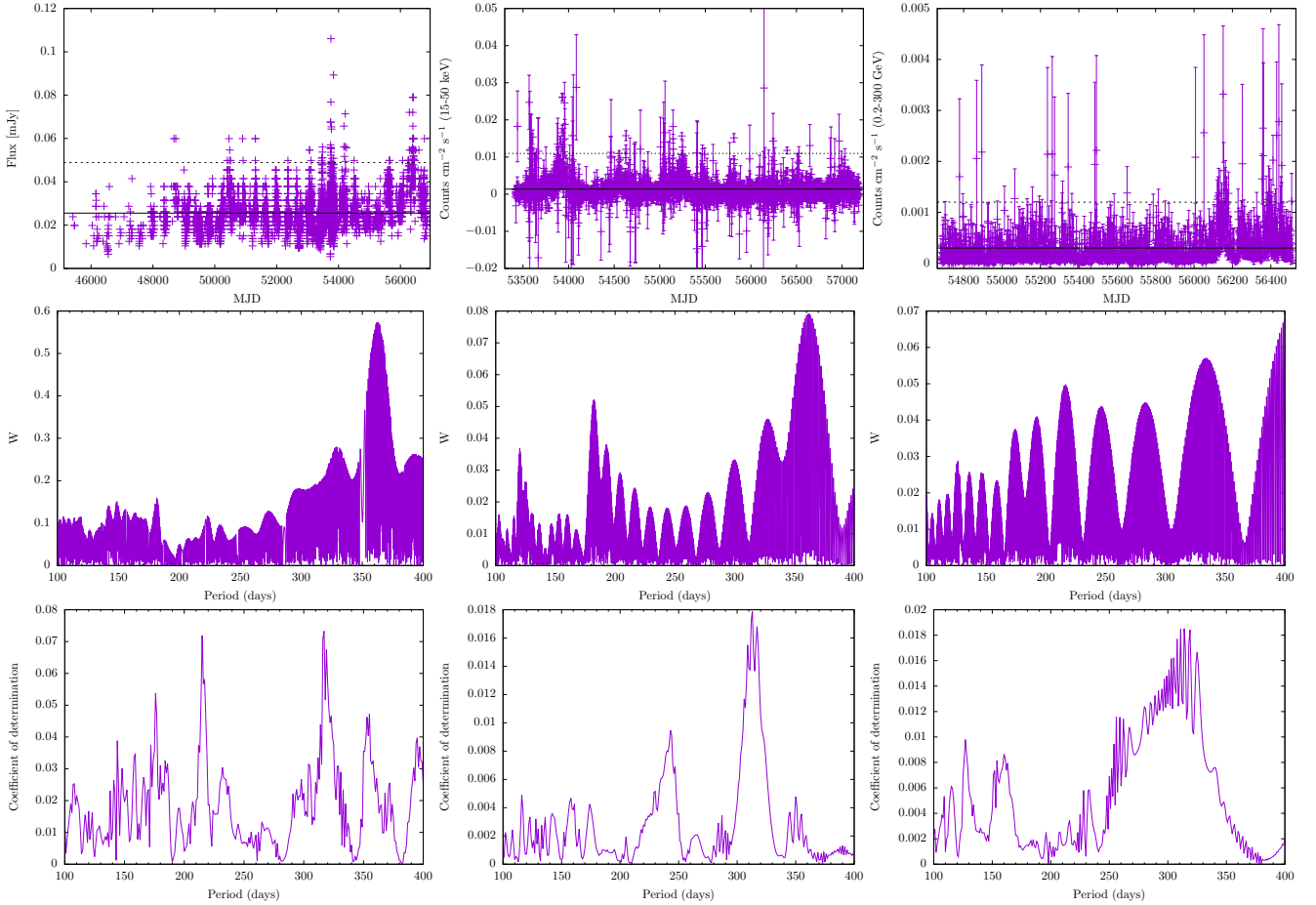


Figure 1. From left to right, the figure shows the optical, X and γ -ray lightcurves of the blazar Mrk 421 (top row). The horizontal solid lines mark the mean flux levels and the dotted ones show the $3 - \sigma$ level above the mean, below which the outburstless state is defined. Similarly, the middle row presents the corresponding spectral window functions W (see e.g. Dawson & Fabrycky 2010) associated to the time samplings of the databases. The bottom row presents the periodograms obtained using RobPer for each waveband. The plots on the last two rows were produced using the outburstless data.

variability, typical of random stochastic processes. When taking into account both active (with outbursts) and outburstless states of the light curves, the low frequency oscillation modes show a flicker pink-like noise for the active state and a brown-like noise pattern in the outburstless state. The idea of analysing the outburstless signal in the search for periodicities is inspired by the fact that Mrk 421 has a self-organised flicker noise in the low frequency regime. This is quite probably associated to the emissions from the inner central engine, contrary to what is found in the quasar PG 1302-102 which exhibits a W-damped random walk behaviour (Graham et al. 2015) associated with a brown-like noise. The $1/f$ noise is the result of an infinite superposition of stochastic signals (Eliazar & Klafter 2009b,a) and so, it has no main periodicities associated. In order not to confuse our calculations with any false periodicity in this source, we removed any signal above the $3 - \sigma$ noise level. With this, a brown-like noise in the resulting outburstless state is obtained. Thus, the existence of a highly correlated process such as the inferred eclipsing supermassive binary black hole system appears natural, as in the case of the PG 1302-102 quasar mentioned above.

We conclude with Figure 2 which shows the folded X-ray

light curve using a folding period of 310 days (approximately a 10th of the temporal extent of the data) with corresponding stacked error bars, together with the optimal generalised eclipse model. Notice that having close to 10 cycles allows to appreciate directly the brightening identified by the maximum likelihood model, despite the extremely noisy data. Our results can be interpreted as an eclipse produced by a supermassive black hole orbiting the central engine resulting in a gravitational lensing brightness enhancement.

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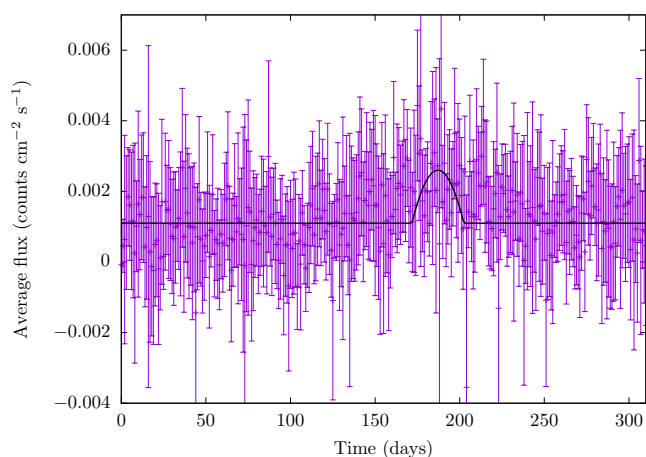


Figure 2. The figure shows the folded light curve of the X-ray data using a period of 310 days, with average error bars. The solid curve is the best fit generalised eclipse found using the maximum likelihood model described, having a peak enhancement of 136%.

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